**Factors Influencing the Eruption of Water-Based Magmas through Europa's Ice Crust.** L. Wilson[1,2] and J.W. Head[2], [1]Environmental Science Division, Inst. of Environmental and Biological Sciences, Lancaster University, Lancaster LA1 4YQ, U.K. L.Wilson@ Lancaster.ac.uk, [2]Department of Geological Sciences, Brown University, Providence RI 02912, U.S.A. James_Head@Brown.edu

We explore the factors which control the melting of ice by silicate magmas at the base of the ice crust of Europa and the ability of the resulting fluids, which may contain some proportion of fragmented silicate material, to reach the surface through dikes. We find that fluids carrying significant proportions of silicate clasts can only reach the surface if the ice layer is less than ~15 km. Fluid discharge rates up to 2 x $10^4$ $m^3$ $s^{-1}$ from fissure vents up to ~15 km long are likely.

One option for the generation of liquid water at depth in the ice crust of Europa is the migration of silicate magma through the silicate lithosphere to the rock-ice boundary. Intimate mixing of the magma with shattered ice in the contact zone in the equivalent of sub-surface phreatomagmatic activity would lead to the maximum transfer of thermal energy from magma to ice. The accompanying chilling and fragmentation of the magma would provide mm-sized silicate clasts which could be transported to the surface by the rise of the water fluid.

The thermodynamic consequences of mixing equal volumes of fragmented silicate magma and fragmented ice at the base of an ice crust are shown in Table 1 for a range of ice crust thicknesses L. Pressures in the interaction zone are taken to be about 10% greater than lithostatic in anticipation of the excess pressures needed to keep open fractures (dikes) to the surface. In all cases where the pressure is sub-critical, a mixture of water liquid and water vapor is formed. For vapor volume fraction greater than ~80% the vapor is the continuous phase entraining water liquid droplets and silicate clasts; for lower volume fraction the liquid carries vapor bubbles and clasts. Efficient entrainment is only possible if the rise speed of the continuous phase exceeds the terminal fall velocity of the clasts and also if the rise (vapor bubbles) or fall (liquid droplets) speed of the discontinuous water phase is small. We therefore need to know the rise speed, U, of the water fluid-silicate mixture in the dike leading to the surface.

This rise speed will be dictated by the excess pressure $P_a$ in the ice melting zone at depth L, the density $\rho_c$ of the ice crust, the bulk density $\rho_m$ of the resulting water fluid plus entrained silicates, the acceleration due to gravity g, and the volume flux F of silicate magma arriving from depth in the lithosphere. The relationship [1] between the mean dike width $D_m$ and $P_a$, $\rho_m$, $\rho_c$, L, g and the elastic properties of the ice crust, Poisson's ratio $\nu$ and shear modulus $\mu$ is

$$D_m = [(1-\nu)/\mu]\ L\ [(\pi/2)P_a + (Lg/3)(\rho_m-\rho_c)]$$

The pressure gradient driving fluid motion is

$$P_m/L = (P_a/L) - g(\rho_m-\rho_c)$$

and the fluid rise speed is

$$U = \{[D_m\ (P_m/L)]/[f\ \rho_m]\}^{1/2}$$

where f is a friction factor close to 0.01 [2] for the high-Reynolds number flows relevant here. The final requirement, since we assume that silicate magma and ice mix in equal volumes, is that the fluid volume flux flowing up the dike in the ice crust, $F = (U\ D_m\ Z)$, where Z is the dike length along horizontal strike and we assume $Z \approx L$, shall match the magma volume flux from depth. This can be estimated using formulae developed for isolated dikes rising from partial melt zones in the mantles of small planetary bodies [3]:

$$F/Z_s = [K_s^4\ \pi^3\ (1-\nu_s)^3]/[768\ \eta_s\ \mu_s^3]$$

where $K_s$, $\nu_s$ and $\mu_s$ are the apparent fracture toughness, Poisson's ratio and shear modulus for silicate rocks (~$10^8$ Pa $m^{1/2}$, 0.25 and 3 GPa, respectively), $\eta_s$ is the silicate magma viscosity (we assume a mafic magma with $\eta_s$ ~10 Pa s) and

$$Z_s = 2\ [K_s/(g\ \Delta\rho)]^{2/3}$$

where $\Delta\rho$ is the density difference between liquid and solid silicate, ~ 300 kg $m^{-3}$. For Europa, $Z_s$ ~ 8 km and F ~ 2 x $10^4$ $m^3$ $s^{-1}$.

Combining the above expressions allows us to construct the models given in Table 2 in which we assume values for the depth of melting L and bulk erupting fluid density $\rho_m$, and solve for the pressure $P_a$ in the melting zone, the mean width of the dike $D_m$, the pressure $P_m$ driving the eruption and the fluid rise speed U. Given U, we can predict the diameter $\phi$ of the largest silicate clast which can be supported by the continuous water phase by equating the fluid drag force to the clast weight. If this predicted size exceeds the likely mean clast size (~1 mm) the model solution is self-consistent when we assume that the water fluid can transport all of the silicates and choose $\rho_m$ accordingly. This is

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the case for L = 1 km and 3 km in Table 2. If the predicted size is much less than the likely mean clast size, the self-consistent models are those for which we assume that no silicate clasts are carried, as is the case for L = 60 km and 90 km in the table.

For intermediate melting depths, neither extreme assumption is valid. The entries for L = 10 and 30 km in the table are for erupting fluid densities such that the fluid is neutrally buoyant, and correspond to ~15% of the silicate clasts being entrained. For L = 10 km the value of $\phi$ is marginally consistent with 15% of the silicates being transported, and for L = 30 km it is not. This strongly suggests that the maximum depth from which silicate material with a mean grain size of order 1 mm can be carried to the surface is closer to 10 km than 30 km.

The implication is that if surface deposits from eruptions of water-based fluids on Europa are found to contain a significant proportion of silicates, this will imply that the thickness of the ice crust in the vicinity of the vents does not exceed ~15 km. Also, the values given earlier for likely silicate magma supply rates from the mantle driving such events suggest that total water fluid eruption rates will take values of order 1 to 2 x $10^4$ $m^3$ $s^{-1}$, and that the discharge rates per unit length along strike of active fissure vents will span the range 1 to 20 $m^3$ $s^{-1}$ $m^{-1}$.

References: [1] Weertman, J. (1971) JGR 76, 1171-1183. [2] Wilson, L and Head, J.W. (1981) JGR 86, 2971-3001. [3] Wilson, L and Keil, K. (1996) JGR 101, 18927-18940.

Table 1. For various thicknesses L in km of Europa's ice layer the temperature $T_f$ in Kelvins and the pressure in MPa resulting from mixing of mafic silicate magma and ice are shown, together with the liquid and vapor mass fractions, the vapor volume fraction, and the densities in kg $m^{-3}$ of the various phases, including an equal volume mixture of silicate fragments and water fluid.

| Pressure | L | $T_f$ | liquid fraction | vapor fraction | liquid density | vapor density | vapor vol. fraction | bulk fluid density | fluid-silicate bulk density |
|---|---|---|---|---|---|---|---|---|---|
| 4.4 | 1 | 530 | 0.37 | 0.63 | 789 | 22 | 0.984 | 35 | 1467 |
| 7.6 | 3 | 565 | 0.46 | 0.54 | 728 | 41 | 0.955 | 72 | 1486 |
| 17.0 | 10 | 625 | 0.73 | 0.27 | 565 | 119 | 0.642 | 279 | 1590 |
| 38.0 | 30 | 625 | supercritical | | 545 | 545 | - | 545 | 1722 |
| 71.0 | 60 | 620 | supercritical | | 1018 | 1018 | - | 1018 | 1960 |
| 107.0 | 90 | 620 | supercritical | | 1534 | 1534 | - | 1534 | 2217 |

Table 2. For a range of ice crust thicknesses L in km and bulk fluid densities $\rho_m$ in kg $m^{-3}$, values are given for the excess pressure $P_a$ in MPa holding the dike open, the mean dike width $D_m$ in meters the pressure $P_m$ driving fluid flow, the mean fluid rise speed U, the density $\rho_f$ in kg $m^{-3}$ of the fluid phase supporting clasts, and the maximum clast diameter $\phi$ that can be carried upward.

| L | $\rho_m$ | $P_a$ | $D_m$ | $P_m$ | U | $\rho_f$ | $\phi$ |
|---|---|---|---|---|---|---|---|
| 1 | 1467 | 2.96 | 1.2 | 2.25 MPa | 13.7 m/s | 22 | 570 mm |
| 3 | 1486 | 2.26 | 3.2 | 41.9 kPa | 1.74 m/s | 41 | 17 mm |
| 10 | 917 | 0.256 | 1.0 | 0.256 MPa | 1.67 m/s | 565 | 220 mm |
| 30 | 917 | 0.085 | 1.0 | 85 mPa | 558 mm/s | 545 | 24 mm |
| 60 | 1018 | 7.88 | 225 | 4.2 mPa | 1.2 mm/s | 1018 | 24 µm |
| 90 | 1534 | 72.19 | 3093 | 1.6 µPa | 60 µm/s | 1534 | 5.4 µm |